DAWN Coherent Wind Profiling Lidar Flights on NASA's DC-8 during GRIP

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1. Introduction

Almost from their invention, lasers have been used to measure the velocity of wind and objects; over distances of cm to 10s of km. Long distance (remote) sensing of wind has been accomplished with continuous-wave (CW), focused pulsed, and collimated pulsed lasers; with direct and coherent (heterodyne) optical detection; and with a multitude of laser wavelengths.

Airborne measurement of wind with pulsed, coherent-detection lidar was first performed in 1971 with a CW CO_2 laser[1], in 1972 with a pulsed CO_2 laser[2], in 1993 with a pulsed 2-micron laser[3], and in 1999 with a pulsed CO_2 laser and nadir-centered conical scanning[4]. Of course there were many other firsts and many other groups doing lidar wind remote sensing with coherent and direct detection.

2. NASA's Requirement

NASA frequently commissions the National Research Council (NRC) to provide external advice to NASA. The first NRC Decadal Survey for earth science mission advice to NASA was published in 2007[6]. The NRC recommended 15 priority earth science missions for NASA implementation. One of these missions is global measurement of vertical profiles of the horizontal wind magnitude and direction, tersely called "3D Winds". The NRC report agreed with the conclusions of previous studies by NASA and NOAA that the optimum sensor to provide the wind measurements is hybrid pulsed wind profiling lidar[7]. Hybrid refers to having both coherent and direct detection wind lidars working in tandem to take advantage of their complementarities in covering the troposphere. NASA has been developing both of these sensors for many years.

Since NASA's space missions are very expensive, NASA is very sensitive to the risk to the mission of the proposed technology. Proposals must show a sufficiently high technology readiness level (TRL) of each technology. In practical terms, for lidar systems headed to space, NASA prefers airborne demonstration of very similar technology; and measurement technique, sensitivity, and accuracy as is being proposed for space.

Space simulations indicate the coherent 2-micron laser must produce 250 mJ at 5-10 Hz.

NASA Langley Research Center (LaRC) has been developing the pulsed 2-micron laser needed for the coherent-detection half of the hybrid wind lidar of the 3D Winds mission since the 1980's. LaRC has advanced the laser technology is many ways. For example, LaRC advanced the 20 mJ pulse energy state of the art when the program started to 1200 mJ at 2 Hz[8] and 355 mJ at 10 Hz.

In addition to the science motivations of flying our Doppler Aerosol WiNd (DAWN) lidar system during NASA's hurricane Genesis and Rapid Intensification Processes (GRIP) flight campaign, we were also motivated to more closely approach an airborne demonstration of the technology and wind measurement technique being proposed for space.

3. DAWN Coherent Wind Lidar System

The laser is the heart of any lidar system. Our pulsed laser was developed at LaRC. A packaged, compact version was utilized for the DC-8 flights. Table 1 gives the laser parameters of the packaged version. In addition to the laser, other subsystems of a lidar system are the receiver/detector, the small optics, the large

Table 1. DAWN Pulsed Laser Parameters		
Crystal	Ho:Tm:LuLiF	
Architecture	MOPA	
Resonator	Folded	
Amplifiers	1 using 1 pass	
Crystal Shape	Cylindrical	
Pumping	LDAs	
Pumping Geometry	Side	
Seeding Technique	Ramp and Fire	
Pump Wavelength	792	nm
Laser Wavelength	2.05	Microns
Pulse Energy	250	mJ
Pulse Rate	10	Hz
Pulse Duration	180	ns
Pulse Spectrum	~ transform limited	
Pulse Spatial M^2	< 1.2	
Polarization	Linear	

optics, the controlling electronics, and the data acquisition and processing electronics. Table 2 provides further optical parameters of the DAWN lidar system.

Table 2. DAWN Lidar Optical Parameters		
Receiver Location	Opposite side of laser optical bench	
Transmit Receive Switch	Polarizing beam splitter and quarter wave plate	
Optical Detection	Coherent (heterodyne)	
Heterodyne Det.	Dual balanced	
Detectors	InGaAs, RT, 2 ea	
Telescope Diameter	15	cm
Telescope Type	Afocal, off-axis, reflective	
Receiver BW	10 – 180	MHz
Scanner Type	Rotating wedge	
Nominal Beam Deflection	30	deg
Scanning Field of Regard	Conical, apex at lidar, nominally centered on nadir	
Scanning Method	Step-stare	
Lidar Container	Sealed cylinder	
Beam Exit	Window	

Table 3 provides details about our accommodation on the DC-8 aircraft.

Table 3. DC-8 Accommodation		
DC-8 Port	#7, nadir centered	
Port Cover	External, motorized	
Lidar Location	Cargo level	
Electronics Racks	1 in cargo, 2 in passenger level	
Operator Stations	2 people required. Laser station, laser chillers station, data acquisition station	

The laser station and data acquisition stations are shown in Fig. 1 below. The lidar optics cylindrical container is shown over Port 7 in Fig. 2.

Fig. 1: Laser and Data Acquisition Operator Stations

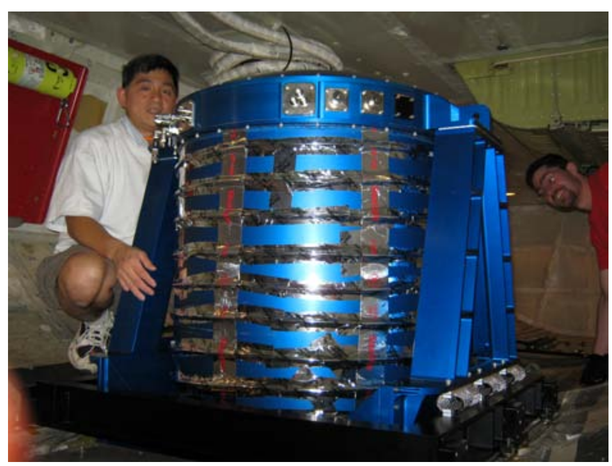

Fig. 2: The DAWN Lidar Optics Canister Containing Laser, Receiver, Telescope, and Scanner

Our lidar scanner permitted programmable laser beam aiming anywhere on the surface of the 30-deg half angle cone. We command the scanner to stop at a given direction to permit multiple lidar shots to be combined into one line-of-sight (LOS) velocity profile. Although we tried many values of the shot accumulation time during GRIP, our nominal scan pattern consisted of 5 azimuth angles (-45, -22.5, 0, 22.5, and 45 deg) centered on the forward direction of the fuselage. We did not look aftward during GRIP due to concerns about scanner rotation time and lost data. But having both aft and fore views is the optimum approach and we plan to do that in the future. Our nominal shot accumulation time was 2 sec, permitting 20 laser shots to be combined. The nominal shot pattern is shown in Fig. 3 below.

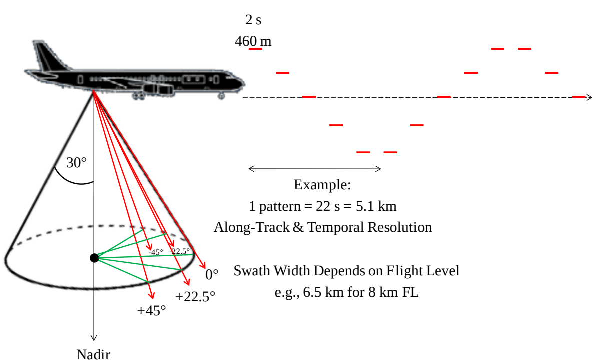

Fig. 3: Nominal DAWN Scan Pattern

Fig. 3 shows an oblique view (left) of the conical scan field of regard, and a top view (right) of the scan pattern. The 5 azimuth angles are represented by the 5 red slanting lines. Their projections into the horizontal are the 5 green lines. The red dashes represent the extent in space of the LOS wind profile shot accumulation. The DC-8 flies approximately 460 m in 2 sec. We depict a 2 sec interval for the scanner to change azimuth angles. Note that the scan pattern goes both up and down in angles, alternating which extreme angle begins a scan pattern. In this example the horizontal wind profile is derived from the 5 azimuth directions. It has a 5.1 km (22 sec) along-track horizontal resolution. The cross-track width of the 5 azimuth angles depends on measurement altitude and DC-8 altitude. Assuming 0 km and 8 km, respectively, gives a width of 6.5 km.

In principle, only 3 azimuth directions are needed to measure horizontal vector wind, and vertical wind magnitude. However, there are several possible unknown offsets which must be determined using land returns. For this reason, more that 3 azimuth angles are desired. A second reason for more azimuth angles is for better wind measurement accuracy.

4. Coherent Detection Pulsed Wind Lidar Figure of Merit

A figure of merit (FOM) is most useful if it measures a quantity that is most important to understanding a sensor's performance. For coherent detection pulsed wind lidar, the required aerosol backscatter level β is much more important than the wind error standard of deviation. This is because the wind error is relatively stable despite large changes in the required backscatter. The portion of the FOM equation that applies to pulse energy E, pulse rate f, and optical diameter D is:

$$FOM \propto \frac{1}{\text{Min. Req. } \beta} \propto E\sqrt{f}D^2$$

Using this FOM, the LaRC DAWN coherent detection wind lidar is the most sensitive (or "most powerful") lidar of its type yet built.

5. Preliminary Data

GRIP DC-8 science flights began on Aug. 17, 2010, and ended on Sept. 22, 2010. There were 25 total flights (3 shakedown, 1 checkout, 6 ferry, and 15 science), and 139 total flight hours (113 science). These were the first ever flights of the DAWN coherent wind lidar instrument, and several problems were encountered. Post GRIP instrument analysis revealed that the telescope secondary mirror was burned, probably for the whole mission. This reduced SNR for the entire GRIP mission by perhaps 10 dB.

Figures 4 and 5 show some preliminary DAWN wind measurements compared to collocated dropsonde measurements. The data were taken on Sept. 1, 2010, near 17:20:15 Zulu time. The DC-8 was at 29.956 N latitude and 75.753 W longitude at 10,609 m altitude and moving at 144 m/s ground speed at bearing 56.5 deg. Since navigation bearings are CW from north, and meteorological angles are "air coming from" CCW from east, a wind with air moving in the same direction as the DC-8 would have a direction label of (90 – 56.5) +180 = 213.5 deg. Since it takes many minutes for the dropsonde to hit the surface, the contemporaneity of the lidar and dropsonde data gets worse as altitude decreases.

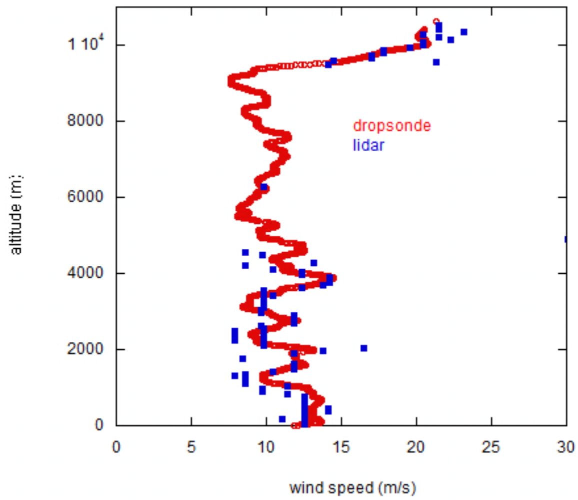

Fig. 4: Comparison of DAWN and dropsonde horizontal wind magnitude.

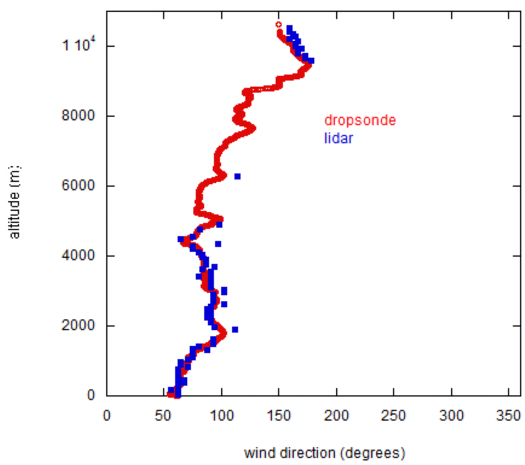

Fig. 5: Comparison of DAWN and dropsonde horizontal wind direction

6. Conclusions

A very large FOM coherent wind lidar has been built by LaRC and flown on a DC-8. However a burn on the telescope secondary mirror prevented the full demonstration of high FOM. Both the GRIP science product and the technology and technique demonstration from aircraft are important to NASA. The technology and technique demonstrations contribute to our readiness for the 3D Winds space mission. The data analysis is beginning and we hope to present results at the conference.

7. Acknowledgements

We gratefully acknowledge the support of NASA Science Mission Directorate (SMD) Earth Science Division (ESD); the NASA SMD ESD Earth Science Technology Office (ESTO), and NASA Langley Research Center.

The authors acknowledge valuable technical work by Yingxin Bai, Bruce Barnes, Frank Boyer, Joel Campbell, Songsheng Chen, Michael Coleman, Larry Cowen, Joe Cronauer, Fred Fitzpatrick, Mark Jones, Nathan Massick, Ed Modlin, Anna Noe, Don Oliver, Karl Reithmaier, Geoffrey Rose, Adam Webster, The-Hwa Wong, and William Wood.

We acknowledge great assistance from the companies Harley & Sons, Nu-Tek Precision Optical Corp., Science Systems and Applications, Inc., Univ. of N. Dakota, and Welch Mechanical Design.

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